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This is the final report on the experimental research performed under U.S. Army Research Office Grant No. DAAL 03-91-0026, with Dr. Thomas Doligalski as the Technical Program Manager. The Principal Investigator was B.R. Ramaprian. The research work involved the measurement of the pressure and velocity fields in the three-dimensional flow field surrounding and in the wake of the tip region of a rectangular wing of NACA 0015 profile. Measurements were made both with the wing stationary and with the wing oscillating sinusoidally in pitch about its quarter-chord axis. Pressure transducers and three-component laser Doppler velocimetry were used in these measurements. The results have been used to understand the vorticity dynamics in three-dimensional steady and unsteady flows. The study is relevant to helicopter rotor aerodynamics. All the data have been archived and are available for use by any interested reader.

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INTERACTIONS OF SPANWISE AND CHORDWISE VORTICITY ASSOCIATED WITH THREE-DIMENSIONAL DYNAMIC STALL OVER AN OSCILLATING WING

Final Report

by

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prepared for

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October 15,1994

ABSTRACT

This is the final report on the experimental research performed under U.S. Army Research Office Grant No. DAAL 03-91-G-0026, with Dr. Thomas Doligalski as the Technical Program Manager. The Principal Investigator was B.R. Ramaprian. The research work involved the measurement of the pressure and velocity fields in the three-dimensional flow field surrounding and in the wake of the tip region of a rectangular wing of NACA 0015 profile. Measurements were made both with the wing stationary and with the wing oscillating sinusoidally in pitch about its quarter-chord axis. Pressure transducers and three-component laser Doppler velocimetry were used in these measurements. The results have been used to understand the vorticity dynamics in three-dimensional steady and unsteady flows. The study is relevant to helicopter rotor aerodynamics. All the data have been archived and are available for use by any interested reader.

STATEMENT OF WORK AND SUMMARY OF RESULTS

The research effort was focused on the understanding of the three-dimensional flow field around and in the wake of the tip region of a rectangular NACA 0015 wing of semi-aspect ratio 2. The effort included measurements of the surface pressure distributions over the wing, as well as velocity measurements over the wing and across the wing tip vortex. The experiments were conducted both with the wing held stationary at incidence and with the wing oscillating sinusoidally about its quarter-chord axis about a mean incidence. The objective of the research project was to understand the generation, evolution and mutual interaction of the spanwise and chordwise vorticity in the tip region, with special attention to the roll of the tip vortex on the flow dynamics. Special focus was also on the roll played by three-dimensionality on the vortex dynamics and flow separation leading to stall in unsteady flow over the oscillating wing. This study has relevance to the aerodynamics of helicopter rotor blades. While there have been other earlier experiments on pressure and force measurements on stationary and oscillating rectangular wings of small aspect ratio, reported in the literature, the present experiments are the first in which pressure measurements are accompanied by extensive velocity measurements using three-component laser Doppler anemometry (LDA).

The experiments were performed in a low-speed open circuit wind tunnel. The wing model of 30 cm chord and 60 cm semispan (nominal values) was mounted from the side wall of the tunnel as a cantilever, with its span horizontal. The wing mounting allowed the wing to be oscillated sinusoidally in pitch about its c/4-axis. Pressure measurements were made using a pressure transducer in conjunction with a finely spaced set of surface pressure taps and a 48-port Scanivalve. Velocity measurements were made using a fiber-optics based, three-component, three-color, six-beam LDA system. The fiber optics cable permitted the mechanical separation of the two "probes" from the rest of the heavy optics. The lightweight probes were traversed by a computer controlled three-dimensional traverse. A schematic of the experimental set-up is shown in Fig.1. The wing model used in the tip-vortex studies during the earlier phases of the project was made from wrapping an aluminum skin around profiled aluminum spars. The geometry of the NACA 0015 profile used for the wing is shown in Fig.2. Seeding required for the LDA was provided by introducing water particles from an ultrasonic humidifier via perforations on the wing surface. Later, this wing model was replaced by a second model of identical NACA 0015 profile. This model was assembled from a set of interchangeable airfoil elements of assorted spans in the range 6-50 mm, each of which was precision machined on a numerically controlled milling machine. One of these elements was instrumented with a finely spaced set of surface pressure taps. The wing could be assembled with the instrumented element located in any desired spanwise position. This design of the model was used in order to allow one to achieve a high spatial resolution of the pressure data without the need to provide an impractically large number of pressure taps.

The experimental program was carried out in the following six phases.

(i) LDA measurements in the wing tip vortex behind a stationary wing
(ii) LDA measurements in the wing tip vortex behind the oscillating wing
(iii) LDA measurements in the near wake of the steady and oscillating wing

(iv) Surface pressure measurements on the stationary wing
(v) Surface pressure measurements on the oscillating wing
(vi) LDA measurements over the suction side of the stationary wing

The work performed during the first three phases formed the Ph.D. thesis of Youxin Zheng. A report based on the thesis has been submitted to ARO. Also, three papers based on this work have been published. Reprints of these publications have already been sent to ARO. The work performed under phases (iv) and (v) formed the M.S. thesis of Janusz Szafruga. Two papers based on this work have been published, reprints of which have been sent to ARO. Two papers have resulted from the work performed under the last phase. One paper has been submitted to the AIAA 12th Applied Aerodynamics Conference at San Diego in June 1995; and the other will appear in the Proceedings of the European Viscous Flow Workshop on Three Dimensional Boundary layers to be held in Emmen, Switzerland during October 28-29, 1994. Manuscripts of both these papers have been sent to ARO. A list of these publications is given at the end of this report.

Since all the above work has already been reported, only a very brief description of each phase will be presented here. This description includes a brief statement of work and a summary of the important results/conclusions. All the experimental data obtained so far have been archived on disk and are available to any interested reader.

It is to be mentioned here that LDA measurements could not be obtained over the oscillating wing during the present project period. This was because (i) the LDA measurements over the stationary wing turned out to be far more difficult and time consuming than originally anticipated, and (ii) more importantly, it was found that we could obtain LDA data of a much higher quality and far closer to the surface than originally deemed possible. Hence, after consultation with the Program Manager at ARO, we decided to concentrate on obtaining an extensive set of high-quality three-dimensional boundary layer data over the stationary wing during the present project period, and to propose measurements over the oscillating wing as a separate one-year project to follow.

The description of the research effort in individual phases (i)-(vi) is presented below.

1. LDV Measurements in the Tip Vortex behind the Stationary Wing

Statement of Work

The object of this study was to understand the formation, roll-up and subsequent evolution of the tip vortex in the near wake. The experiments were conducted at a free stream velocity of about 8.0 m/s, corresponding to a Reynolds number of about 180,000. The data on the three components of the velocity were obtained at incidences of 2, 5, 10 and 15 degrees, and at downstream locations in the region $0.15 < x^*/c < 3.3$, where x^* is the streamwise distance measured from the trailing edge of the wing. At each x^*-station, data were obtained across the vortex at about 500 points which formed a fine grid in the cross-stream plane. The size of the grid was 0.25 cm x 0.25 cm in the inner part and 0.5 cm x 0.5 cm in the outer part. Some pairs of stations (x^*=4, 5; 15,16; 30,32 cm) were selected close to each other, so that derivatives of velocities in the streamwise direction (required for

vorticity calculation) could be obtained accurately. Time-averaged flow properties were obtained from about 1500 samples of data taken at each grid point over a period of about 30 - 120 seconds (depending on the location of the point in the vortex). The three mean vorticity components at each grid point were calculated from the three mean velocity components using first-order finite-difference approximation. In addition, the data were processed to obtain the turbulent stresses at a few selected x*-stations. Measurements at each x*-station lasted typically 10-12 hours. The experimental procedure including probe positioning and data acquisition was fully automated during this period. This study is reported in AIAA Paper No. 91-1685. More details of the study are presented in the thesis of Y. Zheng and also the departmental report by Zheng and Ramaprian (see list of publications).

Summary of the Results

The experimental studies of tip vortex in the near wake of the rectangular wing have resulted in following conclusions:

(a) The shear layer from the trailing edge rolls up into a spiral to form the vortex.
(b) Cross-stream vorticity is rotated into a streamwise direction in the core region of the vortex augmenting the axial vorticity component ω_x.
(c) The vortex core is dominated by ω_x.
(d) The turbulence in the vortex is associated primarily with the spiralled shear layer originating in the more inboard parts of the wake.
(e) Circulation within the viscous/turbulent vortex varies as r^2 (r being the distance from the center of the vortex) in the core region, and follows a semilogarithmic law in the outer region.

2. LDA Measurements in the Tip Vortex behind the Oscillating Wing

The object of this study was to understand the effect of wing oscillation on the formation, roll-up and subsequent evolution of the tip vortex. These experiments were conducted at a freestream velocity (U_∞) of about 8 m/s corresponding to a Reynolds number of about 18,000. The wing was oscillated sinusoidally in pitch about its quarter-chord (c/4) axis by a Scotch-Yoke mechanism driven by a speed-regulated D.C. motor. The mean angle of incidence (α) in these experiments was 10 degrees. The amplitude ($\Delta\alpha$) and frequency (f) of oscillation were 5 degrees and 1 Hz. respectively. The selected oscillation frequency corresponds to a "reduced frequency" k ($= \pi fc/U_\infty$) ≈ 0.1, which is relevant to helicopter rotor-blade aerodynamics. The data on the three components of the velocity were obtained at locations in the region $0.3 < x^*/c < 3.3$ downstream of the trailing edge. The exact locations were 10, 11, 20, 30, 40, 50, 60, 62, 80 and 100 cm from the trailing edge. At each station, measurements were obtained across the vortex at about 500 points which formed a fine grid in the cross-stream plane. The instantaneous velocity components were ensemble averaged over a large number of oscillation cycles (ranging from 50 to 500) to obtain phase-locked values of the three components of the velocity at each point. The spatial resolution of the data was fine enough to allow one to calculate the three phase-locked components of

vorticity at each point across the vortex. In addition, the data were processed to obtain phase-locked values of the turbulent stresses at some selected x*-stations.

This study has been reported in the Proceedings of Eighth Symposium on Turbulent Shear Flows, Munich, September 9-11, 1991. More details of the study are presented in the Ph.D. thesis of Y. Zheng and in the departmental report by Zheng and Ramaprian referred to earlier..

Summary of Results

This study led to the following conclusions:

(a) The mechanism of production and roll-up of the tip vortex is essentially similar to that in steady flow. However, the process is not quasi-steady and exhibits hysteresis.
(b) The wing oscillation effects are convected downstream at a velocity approximately equal to the freestream velocity.

3. LDA Measurements in the Near Wake of the Wing

Statement of Work

In this phase of research, the three-dimensional velocity (and hence the vorticity) field was measured across the entire wake in the tip region (i.e. over a region extending from the tip to about 0.7 chord length inboard) in a cross-stream plane located at a distance of 5 cm downstream of the trailing edge. The object of the study was to understand the three-dimensional nature of the velocity and vorticity fields, and the convection of the vorticity in the downstream direction, in this region. The measurements were obtained both for the stationary wing (at an incidence of 10 degrees)
and the oscillating wing (at oscillation conditions identical to those studied in phase 2 described above). The mean Reynolds number of the flow in both cases was about 180,000. In each case, data were obtained at about 1000 points which formed a fine grid in the cross-stream plane. The data were time averaged for the stationary wing, and phase averaged for the oscillating wing. The velocity data were processed to obtain vorticity and vorticity flux components.

This study has been reported in AIAA Paper No.92-2689.

Summary of Results

In steady flow, the vortex dynamics over the tip region is essentially two-dimensional beyond a distance of about 0.6 chordlength inboard from the tip, even though some cross-flow is still present beyond 0.6c. This flow can therefore be described as quasi-two-dimensional. The vortex dynamics in the case of the pitching wing, however, remains significantly three-dimensional even beyond this region. Also, even at the low reduced frequency of 0.1 studied, the flow exhibits a significant departure from quasi-steady behavior.

4. Surface Pressure Measurements on the Stationary Wing

Statement of Work

These measurements were made not only to study the aerodynamic loading in the tip region, but also to understand the generation of spanwise and chordwise vorticity in this region. Special effort was therefore made to obtain the pressure data with fine enough spatial resolution so that accurate pressure gradients in the chordwise and spanwise directions could be obtained from the measurements. As already mentioned, a second wing model was built for this and subsequent studies. The experiments were conducted mostly at a Reynolds number of 340,000. Chordwise pressure distributions were obtained at spanwise locations corresponding to y/c= 0.03, 0.16, 0.32, 0.49, 0.66, 0.99 and 1.49, using a pressure transducer as already mentioned. The locations of the pressure measurement are shown in Fig.3(a). Data were obtained for a large number of incidences in the range 0-30 degrees. The pressure data were integrated to obtain the aerodynamic coefficients at the different spanwise planes. They were also used to calculate the pressure gradients in the chordwise and spanwise directions, which represent the rate of generation of the spanwise and streamwise components of vorticity respectively, at the wing surface in those planes.

This study has been reported in AIAA Paper No.94-1948. More details of the work can also be found in the M.S. thesis of J. Szafruga.

Summary of Results

(a) At pre-stall incidences, lift gradually decreases with distance from the inboard regions of the wing towards the wing tip, except for the near-tip location (y/c = 0.03) where a significant increase in lift occurs. This increase in lift near the wing tip is accompanied by an increase in the pressure-derived drag and a drop in the pitching moment about c/4..

(b) The drop in lift corresponding to the stall condition (occurring at $17 < \alpha < 18$ degrees) is largest at the far-inboard spanwise location (y/c = 1.49) and decreases towards the wing tip. For post-stall incidences, the lift is largest in the region defined as approximately $0.32 < y/c < 0.49$. For early post-stall incidences (18-21 degrees) a local increase in lift at the near tip location (y/c = 0.03) still exists and finally the lift drops there for $\alpha > 22$ degrees.

(c) Pressure distributions measured at pre-stall incidences on the suction side of the wing at the spanwise location near the wing tip (y/c = 0.03), exhibit bumps located downstream from the negative pressure peak. These bumps in pressure distributions appear to be associated with the infusion of positive chordwise vorticity into the flow from the surface by the action of the spanwise pressure gradient in the tip region.

5. Surface Pressure Measurements over the Oscillating Wing

Statement of Work

These measurements were made primarily to understand the production of spanwise and streamwise vorticity at the wing surface in the three-dimensional unsteady flow over the

tip region. The mean Reynolds number of the flow was 340,000. The wing was sinusoidally oscillated about its c/4-axis around a mean angle of incidence of 15 degrees. The amplitude ($\Delta\alpha$) of oscillation was 4 degrees. Two oscillation frequencies (f) , 1 Hz and 2 Hz were studied. These correspond to "reduced frequencies" (k) of 0.05 and 0.1 respectively, which are relevant to helicopter rotor aerodynamics. Pressure data were obtained at the same chordwise and spanwise locations as in the steady-flow studies of phase 4 (Fig.3a). The instantaneous pressure data were ensemble averaged over 50 oscillation cycles to obtain phase-locked pressure distributions. These data, in turn, were used to evaluate the phase-locked values of the aerodynamic coefficients and the rate of production of phase-locked vorticity components at the wing surface.

This study has been reported in AIAA Paper No.94-1949. More details of the work can also be found in the M.S. thesis of J. Szafruga.

Summary of Results

(a) Pressure distribution over the wing surface and aerodynamic coefficients calculated by the integration of relevant pressure distributions, show nearly quasi-steady behavior during pitch-up motion of the leading-edge, except that stall is delayed.

(b) Strong frequency-dependent dynamic effects occur during pitch-down motion, and these appear as hysteresis loops in pressure distributions and aerodynamic coefficients. These hysteresis loops are generally larger in the inboard region of the wing and decrease toward the tip.

(c) Three-dimensional effects produce a slightly favorable lift behavior in unsteady flow by reducing the size of the hysteresis loop. This results from the noncatastrophic nature of the separation phenomenon in three-dimensional flow. However, for the same reason, lift contributions from the aft regions of the wing become more significant, resulting in a very large negative pitching moment relative to two-dimensional flow.

(d) Vorticity flux carrying vorticity of sign opposite to that of the tip vortex is fed in to the flow from the surface in the aft part of the wing tip by the action of the spanwise pressure gradient. Also vorticity flux data during pitch-up indicate attached flow and hence appear like an extension of quasi-steady unstalled flow in to post-static stall incidences. During pitch-down, however, strong dynamic effects appear, which include the development of a wavelike pattern in the vorticity flux generated at the surface in the region slightly inboard of the tip, though this effect is negligible at the tip itself.

6. LDA Measurements over the Suction Side of the Stationary Wing

Statement of Work

During the last phase of the research program, very detailed and extensive velocity measurements were made in the three-dimensional boundary layer in the tip region over the suction side of the wing. The Reynolds number of the flow was 335,000. The angle of incidence was 12 degrees. Figure 3(b) shows the locations where velocity traverses were made. Figure 3(c) shows the distribution of the data points along the traverse at each station

in a typical spanwise plane. The data points were distributed in such a manner that all the important changes in the velocity, vorticity and turbulent quantities could be efficiently captured. Also, as shown in Fig.3(c), the traverses were made in the direction normal to the wing surface so as to facilitate comparison with the results of three-dimensional boundary-layer codes. Also, traverses were extended well beyond the conventional "boundary layer" region into the inviscid outer region to provide information on viscous-inviscid interaction. A unique feature of the present measurements is that very reliable data on the three components of velocity have been obtained up to distances on the order of 0.1 mm from the surface. In fact, in many cases, the data could be extrapolated to obtain the direction and magnitude of the wall shear stress vector. The data have also been processed to obtain all the Reynolds stress components at selected locations on the wing.

This work is being presented at the European Viscous Flow Workshop on Three-Dimensional Boundary Layers to be held at Emmon, Switzerland on October 28 and 29, 1994. It will appear in the Workshop Proceedings. Also, a draft paper based on this work has been submitted for presentation at the AIAA 12th Applied Aerodynamics Conference to be held at San Diego during June 20-23, 1995.

Summary of Results

A very detailed set of velocity measurements have been made in the three-dimensional flow over the suction side of the wing-tip region, using non-intrusive three-component LDA. These data have yielded quantitative information on the formation and lift-off of the tip vortex.

The three-dimensional features of the flow can be seen clearly from Figs.4-6 which show the velocity vectors in three typical cross-stream planes A, B, C, corresponding to x/c=0.21, 0.46 and 0.95 (x being the chordwise distance from the leading edge) respectively (see Fig.6b). The length of the arrow in these plots denotes the magnitude (to the same scale of 1 cm= 0.5 nondimensional velocity units in all the three figures) and the direction of the arrow denotes the direction. All the three figures have been drawn to the same scale. It is seen that the velocity in the cross-stream plane generally increases downstream. It is also seen that there is a significant inward flow even at y/c=0.65 in all the three cases. The vertical component of the velocity seen beyond the boundary layer in the inboard region is the result of the n-axis being normal to the local wing surface rather than to the freestream direction. The tip vortex has not formed at plane A. It has just formed at plane B and appears to be centered around the point (0.05, 0.025). The direct effect of the vortex is not significant beyond about y/c=0.2. The vortex has begun to roll up and lift up at plane B. The effective center of the vortex is located at about (0.05, 0.06). There is a strong outboard flow of fluid underneath the vortex which will eventually roll up in to the vortex. The effects of the vortex are now felt up to about y/c=0.3. It can be seen that the crossflow is generally directed inboard everywhere except underneath the vortex after it lifts up, where the local crossflow is directed outboard.

Figure 7 shows a vector plot of the wall shear stress. The length of the arrow represents the magnitude of the wall shear stress and the direction of the arrow denotes the

orientation of the wall shear stress (or equivalently, the orientation of the limiting surface streamline). It is tentatively expected that the magnitude of the wall shear stress is accurate to within 5% and the direction is accurate to within 2 degrees. These accuracy statements, however, need to be confirmed from a more careful analysis of the results. This figure also shows the approximate trace of the vortex over the wing, as observed from the accumulation of the seed particles on the wing surface over a period of time. The information contained in Fig.7 is being used to study the topological features of the flow, as well as in assessing the various models in use for describing the inner layer of three-dimensional turbulent boundary layers.

Thus these measurements show that three-dimensionality of the flow extends up to and possibly beyond 0.6 chord lengths inboard of the tip, even though the direct effect of the vortex are significant over much smaller spanwise region. The velocity measurements reported in this paper complement the surface pressure data obtained on the same wing in an earlier experiment. The comprehensive data obtained are being analyzed to understand the topological features of the flow, and to answer several questions raised in connection with the numerical modeling of three-dimensional boundary layers over wing surfaces.

Scientific Personnel Supported and Degrees Awarded

B.R. Ramaprian	PI
Youxin Zheng	Graduate Research Assistant,Ph.D. completed Dec 92
Janusz Szafruga	Graduate Research Assistant,M.S. completed July 93 Working for Ph.D

Papers Published and Theses completed under ARO Sponsorship

Publications

Liang, X., and Ramaprian, B.R., " Visualization of the Wing-Tip Vortex in Temporal and Spatial pressure Gradients, " *J. Fluids Engrg.*, Vol.113, 1991, pp.511-515.

Zheng, Y., and Ramaprian, B.R., "LDV Measurements in the Roll-Up Region of the Tip Vortex from a Rectangular Wing," AIAA Paper No. 91-1685.

Zheng, Y., and Ramaprian, B.R., "LDV Measurements in the Unsteady Tip-Vortex Behind an Oscillating Rectangular Wing," Proc. of the *Eighth Symposium on Turbulent Shear Flows*, Munich, Germany, Sept. 9–11, 1991.

Zheng, Y., and Ramaprian, B.R., "LDV Measurements in the Three-Dimensional Near Wake of a Stationary and Oscillating Wing," AIAA Paper No. 92-2689.

Zheng, Y., and Ramaprian, B.R., "An Experimental Study of the Wing Tip Vortex in the Near Wake of a Rectangular Wing," Report No. MME-TF-93-1, Department of Mechanical and Materials Engineering, Washington State University, Pullman, WA, July 1993.

Szafruga, J., and Ramaprian, B.R., "Pressure Measurements Over the Tip Region of a Rectangular Wing– Part I. Stationary Wing," AIAA Paper No. 94-1948, 1994

Szafruga, J., and Ramaprian, B.R., "Pressure Measurements Over the Tip Region of a Rectangular Wing– Part II. Oscillating Wing," AIAA Paper No. 94-1949, 1994

Szafruga, J., and Ramaprian, B.R., "Measurements in the Three-Dimensional Flow over the Tip Region of a Rectangular Wing at Incidence," *Proceedings of the European Viscous Flow Workshop*, Emmen, Switzerland, October 28-29, 1994

Szafruga, J., and Ramaprian, B.R., "LDA Measurements Over the Tip Region of a Rectangular Wing," submitted to the *AIAA 12th Applied Aerodynamics Conference*, June 19-22, San Diego, CA, 1995

Dissertations

Zheng, Y., "An Experimental Study of the Wing Tip Vortex in the Near Wake of a Rectangular Wing," Ph.D. Thesis, Department of Mechanical and Materials Engineering, Washington State University, Pullman, WA, December 1992

Szafruga, J., "Pressure Measurements over a Stationary and Oscillating Wing," M.S. Thesis, Dept. of Mechanical and Materials Engineering, Washington State University, Pullman, WA, July 1993.

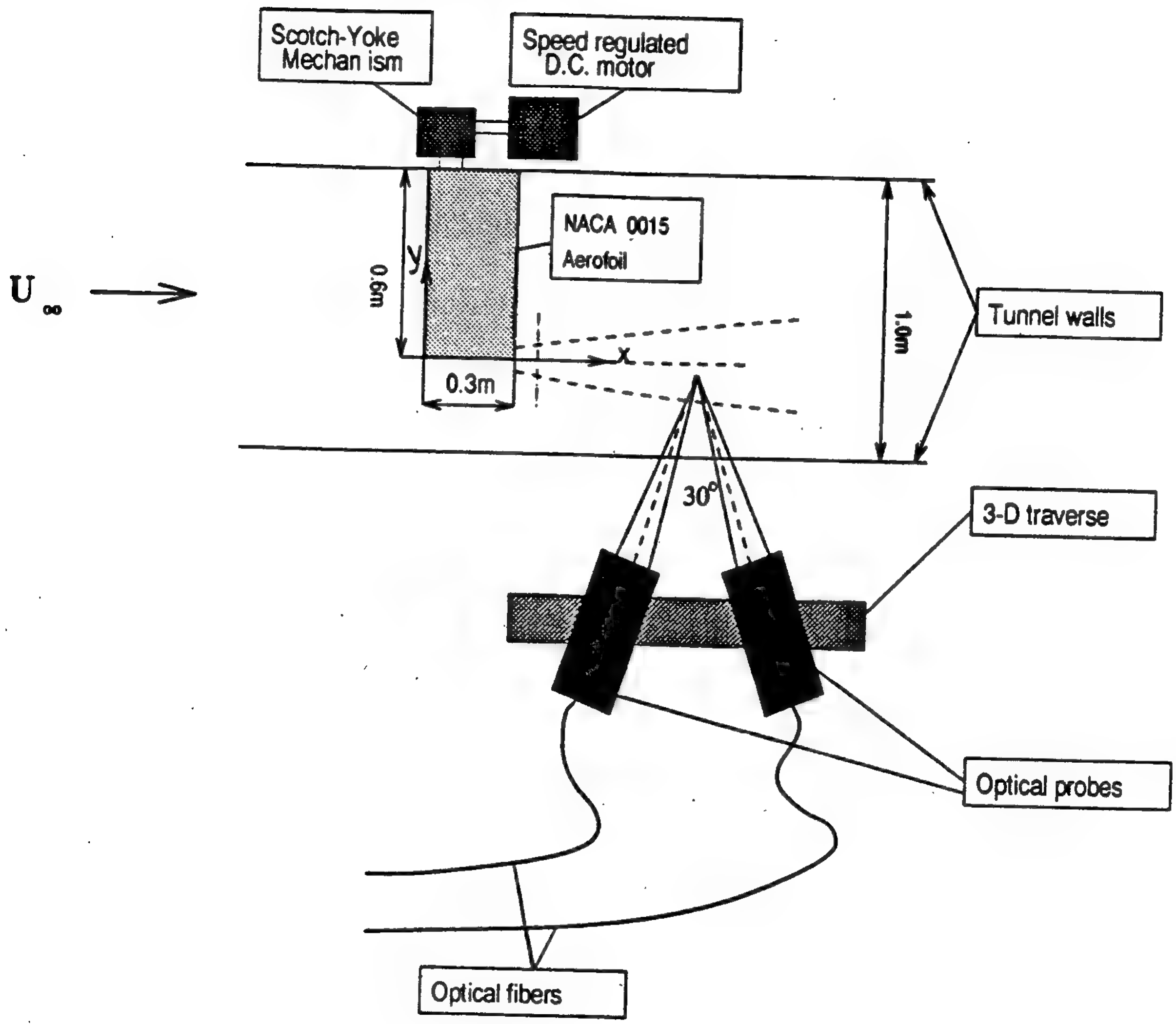
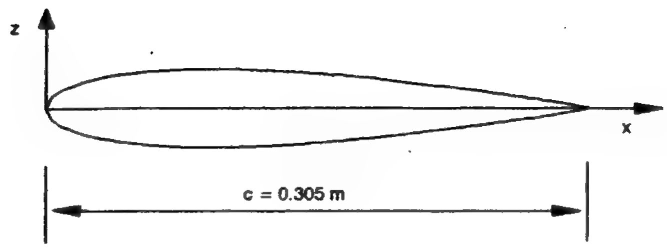


Figure 1 Experimental setup



$$z/c = \pm\frac{t}{0.20}\left(A_1\sqrt{x/c} + A_2(x/c) + A_3(x/c)^2 + A_4(x/c)^3 + A_5(x/c)^4\right)$$

$$t = 0.15 \quad \text{(NACA 0015)}$$

$$A_1 = 0.29690$$

$$A_2 = -0.12600$$

$$A_3 = -0.35160$$

$$A_4 = 0.28430$$

$$A_5 = -0.10150$$

Figure 2 Coordinate system and definition of the NACA 0015 profile

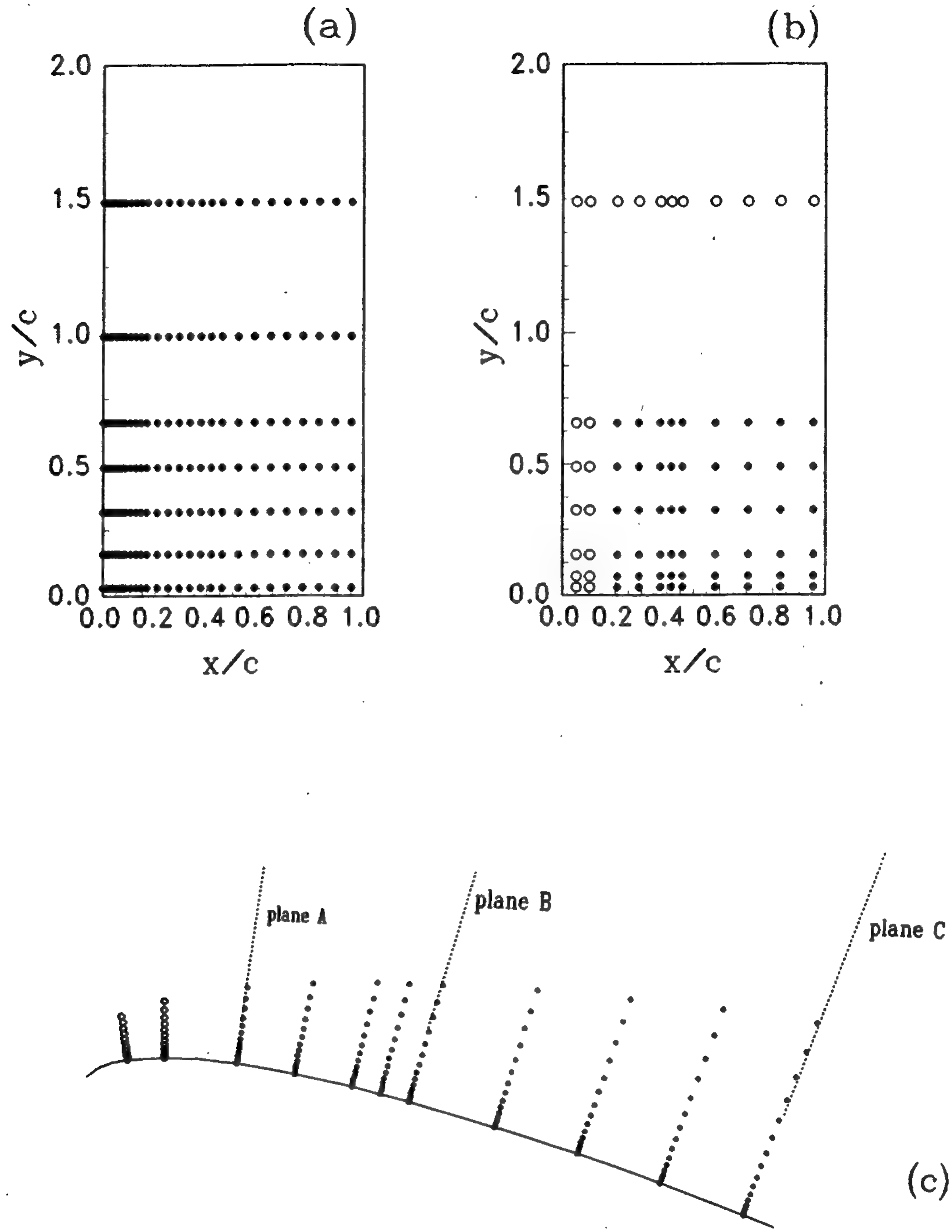


Figure 3 Measurement locations over the suction side of the wing; (a) pressure taps locations, (b) near-surface points of LDA measurements, (c) LDA measurement points at one spanwise location

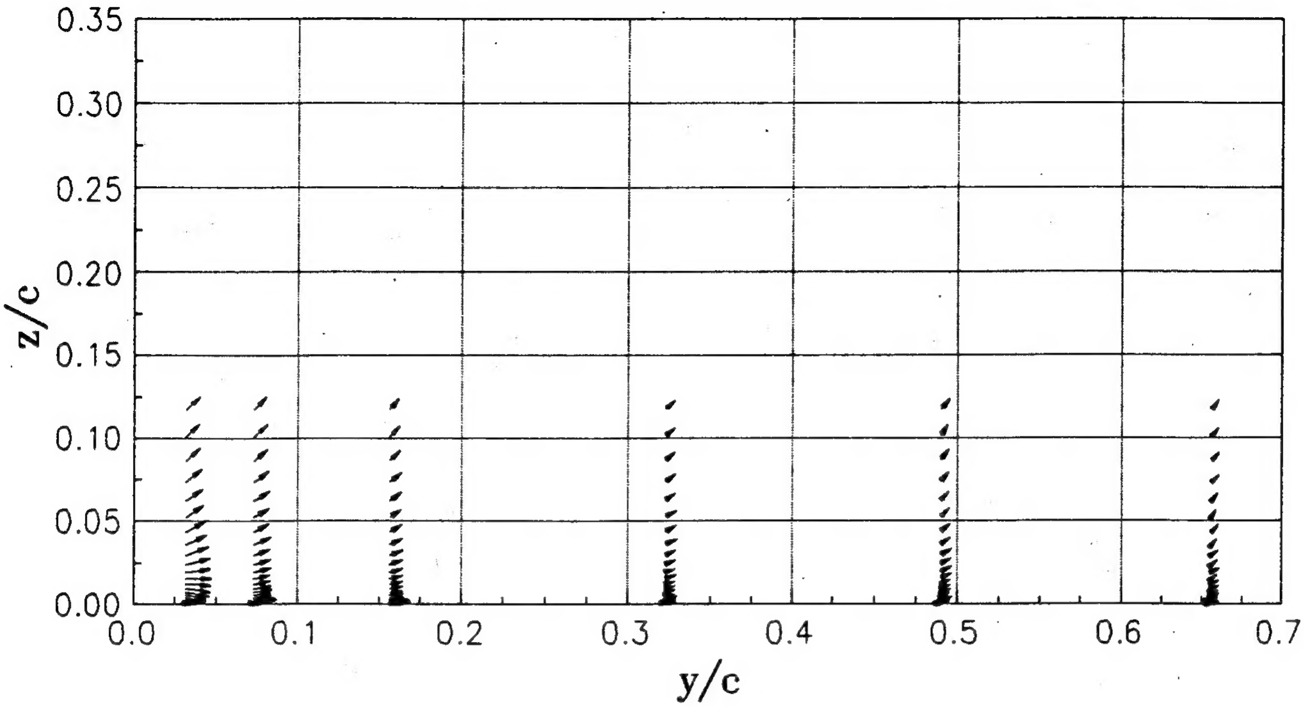


Figure 4 Cross-flow velocity distribution; plane A (x/c = 0.21)

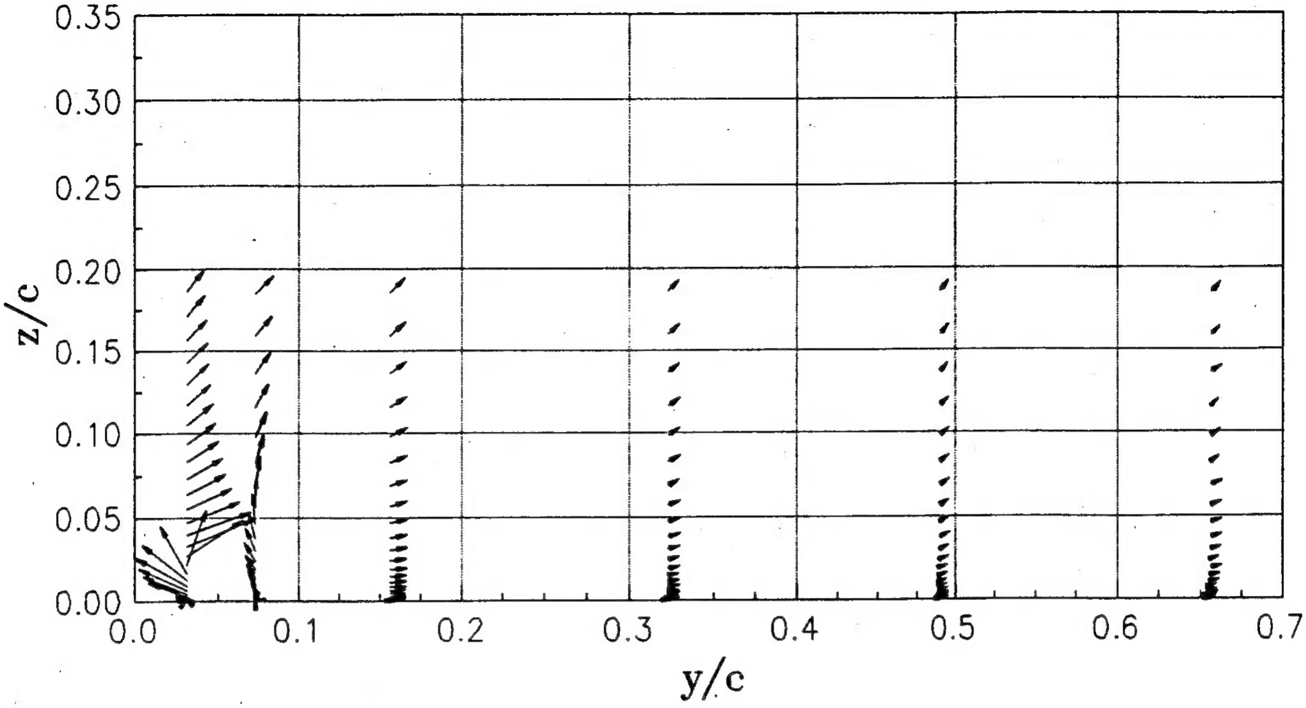


Figure 5 Cross-flow velocity distribution; plane B ($x/c = 0.46$)

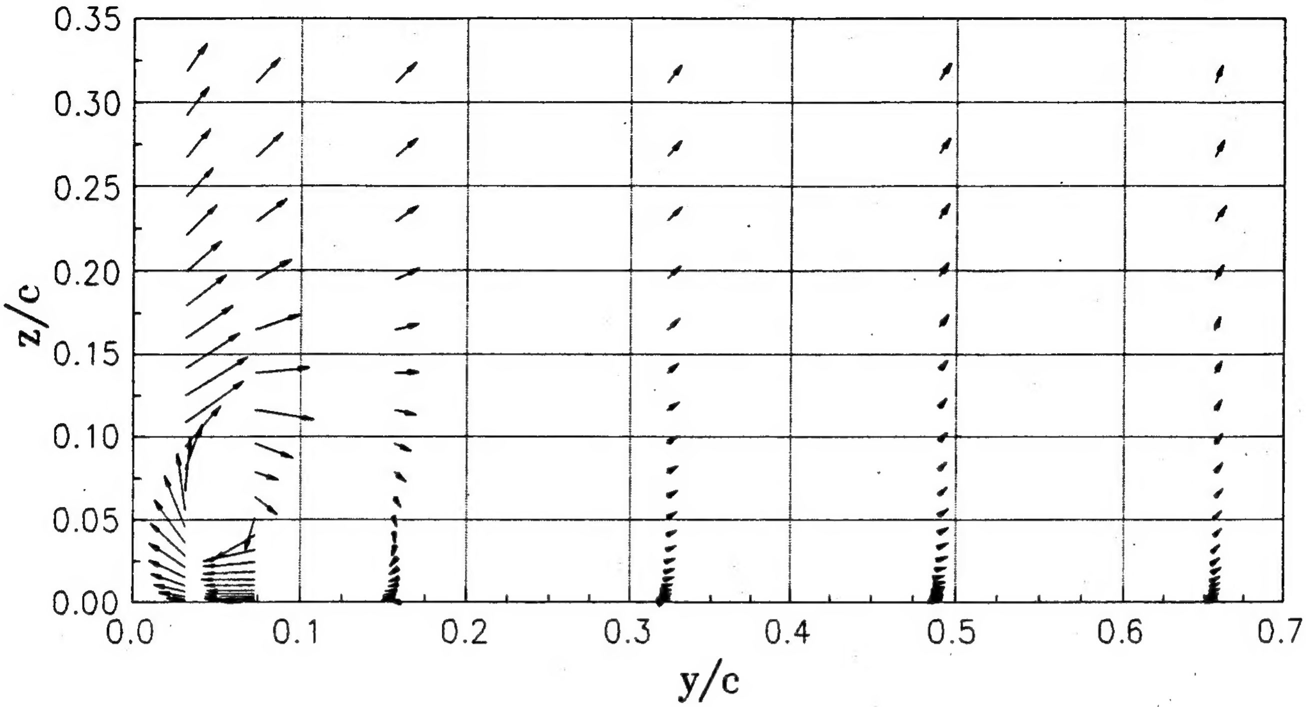


Figure 6 Cross-flow velocity distribution; plane C (x/c = 0.95)

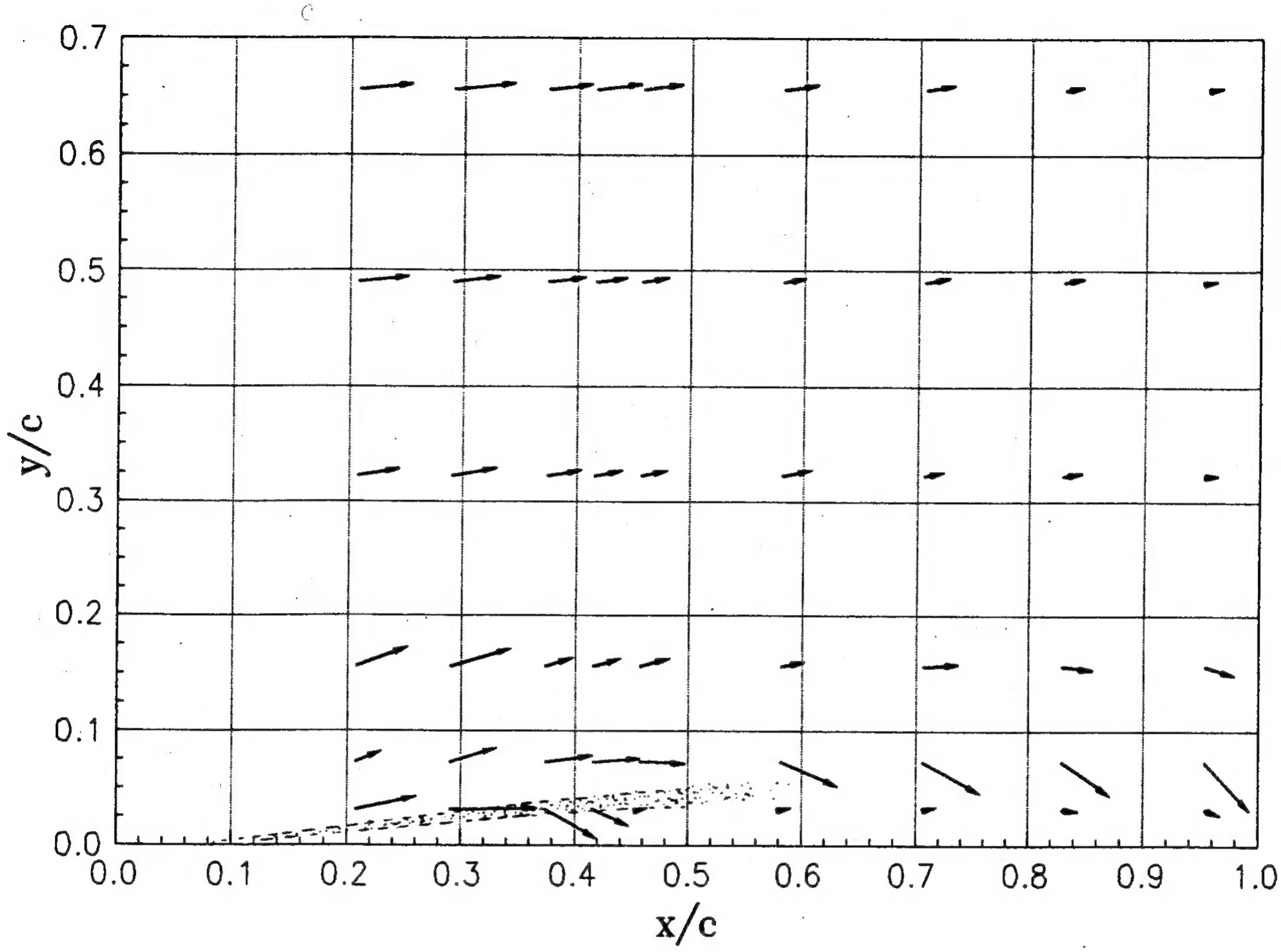


Figure 7 Wall shear stress distribution